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Forecasting sea fog
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Orographic precipitation

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The forecasting of sea fog*

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Summary

This article contains a discussion of the various methods of sea fog forecasting, introducing expert systems to the problem. A practical example from the North Sea is also presented.

1. Introduction

Fog at sea represents a significant hazard to navigation in many parts of the world and has contributed directly to a substantial number of marine safety incidents, including the loss of many lives (Tremant 1987a). At the same time, the forecasting of fog at sea presents substantial difficulties to National Meteorological Services providing forecasts to the maritime community, in view of the general lack of data from ocean areas coupled with the requirement for a close understanding of both the meteorological processes leading to fog formation, advection and dissipation and also the microphysics of the fog itself.

In this article, the navigational aspects of sea fog (Tremant 1987a), and the classification, distribution and physical properties of sea fog, which have been well described by Binhua (1985), are not considered. Only the meteorological forecast methods are presented here.

2. Difficulties in fog forecasting

Like clouds, fog results from the condensation of water vapour in the air, following the effect of various thermodynamic mechanisms. For a given temperature there exists a maximum value (said to be saturated) of the concentration of water vapour; with concentrations greater than this value (i.e. following either a cooling of the air or the presence of additional vapour) there is

* An abridged version of a report in French by Tremant (1987a).

condensation. However the qualitative difference that the appearance of fog produces, corresponds to a very small quantitative difference in water droplet concentration. Thus the saturated concentration in proximity to the surface varies, in general between 5 and 10 g m^{-3} of air, according to the temperature but it only needs an additional supply of the order of 0.1 g m^{-3}, i.e. less than 2%, to create relatively dense condensation.

It is, in large part, for this reason that the numerical methods of weather forecasting, despite their recent progress, are not able at present to correctly forecast fog (as they also fail to forecast visibility in a satisfactory manner). At first, therefore, we are reduced to exploiting the fact that it is known that fog is more likely to appear in certain meteorological situations and to make qualitative forecasts. This is the present situation — at the moment there is no objective method of fog forecasting, either at sea or on land.

Since sea fogs are weather phenomena occurring in the lower atmosphere under the influence of the sea, their formation is related to both the ocean and the atmosphere. In particular, the interaction between the properties of shallow sea and those of the lower atmosphere, both near the air–sea interface, are the dominant effects on the formation, continuation and dissipation of sea fogs. From the view point of the mechanism of sea fog generation, the air–sea interaction is on a small scale, but sometimes we have to consider

the generation from the larger-scale point of view in certain areas with sea fogs.

3. Methods of sea fog forecasting

At present the following five methods for sea fog forecasting are used:

(a) synoptic method,
(b) statistical methods,
(c) numerical models,
(d) instrumental methods, and
(e) forecasting with expert systems.

3.1 Synoptic method

The synoptic method for sea fog prediction has been, and is still being, employed by coastal meteorological stations. To make this prediction, we must have a good forecast of:

(a) wind speed and direction,
(b) air, dew-point and sea surface temperatures, and
(c) the type of fog likely to occur.

Moreover, for coastal fog we must take into account the topography of the location.

3.2 Statistical methods

There is a way of making progress without waiting for the development of numerical forecasting models to reach a state (which could take a long time) in which explicit forecasts of fog for visibility purposes can be made. This method consists of making the hypothesis that there is a link between the presence of fog and certain other meteorological quantities; without trying to understand this link, we try empirically to establish correlations, and on this basis build a method of forecasting.

Despite its indirect nature, this way of working has already proved its effectiveness several times, whether it is a question of forecasting phenomena which are not explicitly taken into consideration by the numerical models, or to adapt these models to a finer spatial resolution. Obviously the chances of success depend on the number of physical reasons for the meteorological quantities in which we are interested (the predictors) to be linked to the quantities we wish to forecast (the predictands), in this case the presence of fog.

3.2.1. The linear parametric discrimination

The linear parametric discrimination is the statistical method most often used for the study of meteorological phenomena.

Fog has been studied in the North Sea (Tremant 1985) and more precisely on Frigg Field (60° N, 02° E). We have used 3-hourly ship observations transmitted over the GTS (Global Telecommunication System). With the help of the results from statistical programs, a very simple method to forecast sea fog was developed:

Condition 1: Air, sea surface and dew-point temperatures are very close (less than 1 °C difference between all three).

Condition 2: Wind direction must be from between 150° and 200°.
Condition 3: Atmospheric pressure must be higher than 1010 mb.
Condition 4: During this study on fog it was possible to deduce that in a 'showers area', that is to say behind a cold front when the shower regime is well established, there is **never** any fog.

When conditions 1, 2 and 3 are satisfied, fog is forecast. When either condition 2 or 3, is not satisfied, then fog is possible as long as condition 1 is met. If condition 4 is the case, there cannot be fog. Condition 4 has priority over all previous conditions. Fig. 1 shows the variation of the temperatures, which are involved in condition 1 along with periods during which conditions 2, 3 and 4 are satisfied, for a specimen duration of 30 days in May 1981 at Frigg Field. There is a close relationship between fog being forecast as probable or possible, and it being observed.

Results obtained by this method of forecasting have been very encouraging — 65% of good forecasts of fog, but the ratio between false alerts and good forecasts was nearly two.

3.2.2 Multiple linear regression

Quinn (1978) has established a set of multiple linear regression equations which describe the distribution of marine fog over a large sea area of the North Pacific Ocean (30–60° N). The predictand is identified as a probabilistic fog parameter whose value is determined from unique combinations of reported present and past weather, visibility and low cloud type or just weather and visibility elements. Thirty-eight model output and climatological predictor parameters are interpolated to each observation point and used in conjunction with the predictand in the development of the regression parameters in each equation, and these are combined with the fog frequency climatological parameter to form an interactive parameter, and a new set of regression equations is derived.

Karl (1978) has described the development and application of a program to forecast important air–ocean parameters using the methods of model output statistics. The focus of this operationally orientated study is to forecast atmospheric marine horizontal visibility using a discrete analysis of observed visibility and the NOGAPS (Navy Operational Global Atmospheric Prediction System) model output parameters. Three strategies (two based on maximum probability and one based on natural regression) are compared to two multiple linear regression methods. The primary data covers from the North American coast and then eastward to about 37.5° W. Both the dependent and independent data were derived from the same basic set. New or unfamiliar concepts, in addition to the primary methodology, include the statistical division of the North Atlantic Ocean into physically homogeneous
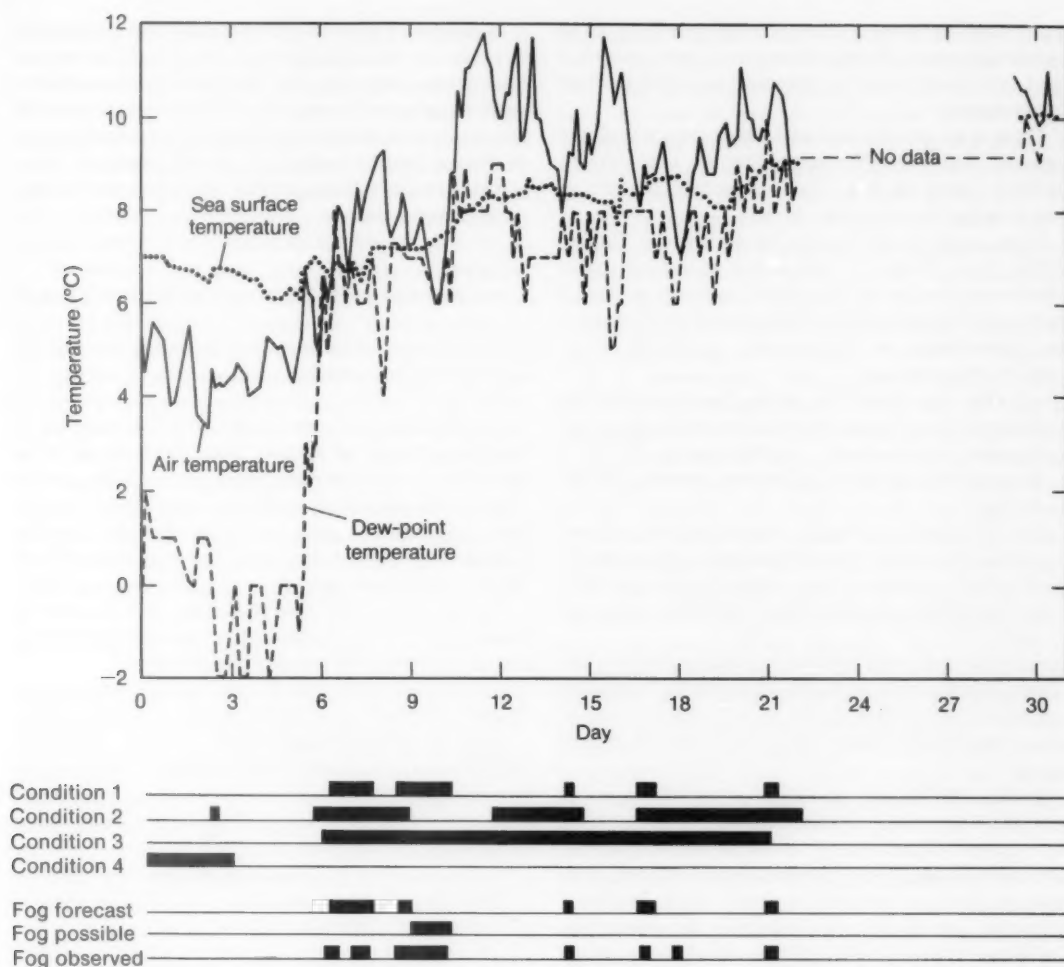
Figure 1. Temperatures recorded on Frigg Field (North Sea) during May 1981; see text for explanation of conditions.

areas, two new threshold models for the application of linear regression equations, linear regression based upon a 'decision tree' concept, functional dependence of predictors and class errors.

The following recommendations are offered for future research:

(a) Investigate the problem of determining the optimum number of equally populated predictor intervals.

(b) Investigate the use of potential predictability in determining the selection of predictors.

(c) Search for better predictors which are particularly suited to visibility prediction.

(d) Investigate other ocean areas and seasons to determine whether the physically homogeneous area scheme is consistent and viable. Develop prediction tables and other aids specifically tailored to region and season.

3.2.3 Other statistical methods used

An algorithm that minimizes the number of errors in linear separation of sets of two different classes has been developed by Polyakov *et al.* (1978). A new method is given by Polkhov and Terziev (1981) for forecasting evaporation fogs on the basis of asynchronous relationships between the thermodynamic state of the atmosphere and the dichotomic variable which takes the value (absence) or (presence) for a given meteorological phenomenon. Quadratic discriminant analysis is used to reveal the relationships.

3.3 Numerical models

Fog formation can result from different causes (radiation, advection, etc.) and it is very difficult to express the role and relative importance of the various processes involved in the formation, development and dispersal of fog. Moreover, a knowledge of the number of droplets of different sizes in a fog is essential to the

understanding of many of the physical processes. In all numerical models, the parameter liquid water content is used, which varies quickly spatially and is very difficult to parametrize.

There is no numerical model which forecasts all the types of fog, but different models are used for the different types of fog. Only numerical models of maritime fog are considered here.

From a model elaborated by Fisher and Caplan (1963), Feit (1972) has built a new numerical model which simulates fog in a maritime environment. In this study, some of the features important to the formation and maintenance of sea fog were evaluated. Some experiments point out:

(a) The importance of taking into account the changes of sea surface temperature gradient along the expected air trajectory — a relative minor change in the gradient may mean a difference between fog and no fog.

(b) The effect an irregular sea surface temperature gradient may have on fog formation — the existence of a warm pocket of water along the air trajectory enhanced the formation of fog in quantity, space and time.

The author states that the further development of the model should concentrate upon the effects of radiation and stability on wind shear. Both of these factors are of prime importance in determining the flux of heat into the sea.

Barker (1977) has described a two-dimensional boundary-layer model. Radiational heat loss along with the transport of static energy, moisture and momentum are treated. Cloud droplet distributions are parameterized using a gamma distribution from which radiative properties and droplet fall velocities are computed. Turbulent exchange coefficients are calculated using the Monin-Obukhov theory of similarity which accounts for variations in atmospheric stability. Although the boundary-layer depth depends only on turbulent intensity during stable atmospheric conditions, its growth during unstable conditions is determined from the intensity of the capping inversion and the amount of turbulence generated at the surface.

Several experiments are presented which demonstrate the effects of various meteorological parameters on the formation and duration of stratus and fog. Energy-budget analyses show the importance of each of the physical processes being modelled. Although not a new idea, radiative transfer processes are shown to be extremely important in the transfer of heat from the boundary layer and in the process of fog formation. Fog formation location is highly sensitive to the moisture content upstream, whereas changes in wind speed have much less effect in the spatial variability of fog location. Numerical experiments with other processes such as downward radiation from the atmosphere, haze and cloud-droplet population are described and shown to have smaller effects.

A paper by Pilié *et al.* (1979) summarizes the results of a study on the formation of marine fog along the California coast. On the basis of observations and analyses, physical models have been formulated for the formation and persistence of at least four different types of marine fog which occur off the west coast:

(a) Areas of fog triggered by instability and mixing over warm water.

(b) Fog developed as a result of lowering stratus cloud.

(c) Fog associated with low-level mesoscale convergence.

(d) Coastal radiation fog advected to sea by nocturnal land breezes.

In addition, it has been found that the triggering of embryonic fogs and further downwind development produces a synoptic-scale fog-stratus system, and is responsible for redevelopment of the unstable marine boundary layer. A major problem in explaining the formation of fog over the ocean is the question of how the air reaches saturation.

Telford and Chai (1984) discuss two aspects of convection over oceans and the following conclusions are derived from theoretical considerations:

(a) The air layer over the sea will usually convect even when the water surface is 10 °C or more colder than the initial air temperature.

(b) An inversion at the level of stratus cloud tops is created by the stratus, and is not a necessary pre-existing condition. Such inversions persist after subsidence evaporates the cloud.

(c) Radiational heat exchange does not play an essential role in stratus formation or maintenance, and can either heat or cool the cloud.

(d) Dry air convection does not erode inversions at the top of the convecting layer.

(e) Fogs are most likely to form at sea where the water is coolest and need no radiation effects to initiate cooling or a boost from patches of warmer water, to begin convection.

(f) Both stratus cloud growth, and the evaporation of clouds by cloud-top entrainment, readjust the vertical structure of the air to leave a constant wet-bulb potential temperature with height.

These conclusions are supported by, firstly, a convective model which has been developed and which shows that vapour-driven convection over the ocean will proceed with zero or negative heat fluxes, at rates which saturate the lowest layer of the atmosphere in a few hours to altitudes of many tens of metres. Secondly, the availability of condensed moisture at the top of the surface layer cools the warmer entrained overlying dry air parcels so that when they descend they are no warmer than the sea surface temperature, and this induces downward moving plumes. This occurs if the wet-bulb potential temperature of the overlying air is less than the

sea surface temperature, even if it is 10 °C or more warmer than the dry-bulb temperature.

Musson-Genon (1987) has developed a one-dimensional boundary-layer model to simulate a fog event. This model described the condensation processes at sub-grid-scale, the gravitational settling of fog droplets and their interactions with solar and thermal radiation, as well as the turbulent transport associated with turbulent kinetic energy.

The different parametrizations used are rather simple, aimed at operational forecasting. The model seems to be able to describe the mechanisms occurring in fog evolution from its appearance to its disappearance. The data set is one of the most complete ever published, but as yet it is difficult to validate the different parametrizations. Nevertheless, the importance of turbulent transport is emphasized. The sensitivity of the model to thermal cooling, the gravitational settling velocity and the initial data are described together with the usefulness of sub-grid-scale parametrization. In this work emphasis has been placed on the quantitative comparison between computed and observed evolutions.

3.4 Instrumental methods

3.4.1 Lidar

A method of determining the predictors of the formation and dissipation of radiation fogs by means of lidars is presented by Tyabotov and Tikhonov (1982) and the possibilities of its practical use are evaluated. It is shown experimentally that the ratio of the scattering coefficients at wavelengths 1.06 and 0.53 micrometres and the degree of polarization of the lidar radiation backscattered by atmospheric aerosol, are observed to differ during formation and dissipation of fog. Such a difference in the indicated parameters occurs as a consequence of a change in the size and shape of the particles during condensation of water vapour or as a result of evaporation of droplets, and also upon a change in the optical density of the medium.

3.4.2 Satellite images

For some years satellite images have been used routinely in operational weather forecasting as a means of detecting the positions and development of cloud systems and for analysing their characteristics. Systems have been developed which present the image on a display screen and which have sufficient interactive capability to allow enhancement of each image through changes to the grey-scale contrast, magnification, etc. Also, increasing use is envisaged for colour display systems to extend further the amount of information which can be conveyed with a single image.

Detection of fog during the daytime is relatively straight-forward using conventional visible and infra-red images. Areas of fog are characteristically bright in the visible image since, in common with most other types of cloud, they strongly reflect solar radiation at visible wavelengths.

In contrast to other forms of cloud, however, fog and low stratus appear relatively warm on infra-red images since their temperature is close to that of the underlying land or sea surface. It is because of the latter characteristic that detection of fog on satellite images is difficult at night when visible images are not available. The thermal contrast between the fog top and the surface is usually very small, and, even where this is measurable, it is often difficult to distinguish changes in temperature caused by the presence of fog from spatial variations in surface temperature.

Eyre et al. (1984) have studied a method of detecting fog at night using a combination of infra-red images at different wavelengths. The variation of emissivity with infra-red wavelength exhibited by fog is used to distinguish it from land or sea surfaces at similar temperature. An interactive image display system has been used to provide a false-colour representation of a combination of the Advanced Very High Resolution Radiometer (AVHRR) images at 11 and 3.7 micrometres in such a way as to highlight areas of fog and low stratus cloud.

In their paper, Eyre et al. have demonstrated the detection of fog and low stratus at night using channels 3 and 4 of the AVHRR imagery. This technique is expected to have considerable potential for application in operational weather forecasting. In addition this work provides an example of one particular application of full resolution digital AVHRR data and illustrates the wealth of information which can be extracted from the images with suitable processing and interactive display techniques.

3.5 Forecasting with expert systems

Investigation into the use of artificial intelligence began in 1956. At the beginning, researchers sought to produce general programs which could solve any problem. Many difficulties arose and researchers turned their attention towards expert systems doing more specialized work.

3.5.1 'Ideal' characteristics of an expert system

Modularity of knowledge: Information from experts in the subject is programmed in a non-structured fashion.

Modification of rules: Rules initially supplied by experts can be easily modified or suppressed, and new ones inserted.

Simplicity of operation of the system: The quality of the man–machine interface is very important. An unqualified person should have no problem in using the system.

Quality of the system: Uncertain information and approximate estimations must be able to be handled. The result must be given as quickly as possible and the number of questions presented to the operator must be as small as possible.

3.5.2 Structure of an expert system

An expert system generally comprises:

A language for expressing expert knowledge: This should be as close as possible to everyday language.
Knowledge base: All the 'production rules' and facts necessary for the correct operation of the system should be included in the knowledge base.
Pattern directed inference system (PDIS): The active element of the system is a program which exploits knowledge stocked in the base, interprets it and works out a final diagnosis.
Complementary functions: These are dialogues with the operator about explanations and the 'path' of reasoning which help correct errors.

3.5.3 Why an expert system?

Compared with a traditional program the advantages are numerous (Tremant 1987b):

(a) Production rules are introduced without a pre-arranged pattern whilst in traditional programs the representation of knowledge is intimately connected to the sequence of instructions,

(b) the same PDIS can be used to activate several knowledge bases in very different domains. For traditional programs, one program is necessary per domain,

(c) the control of knowledge is completely independent of the knowledge itself in an expert system: in traditional programs this control is set in the structure of the program,

(d) adding new rules poses no problem for an expert system; in traditional programs it is sometimes practically impossible,

(e) production rules for expert systems are easily understood by the operator, which simplifies his work.

The use of expert systems in meteorology is described in greater detail by Conway (1989).

3.5.4 Example of an expert system used to forecast fog

A statistical study showed that it would be very difficult to build a physico-statistical model of fog forecasting at sea. On the other hand, a pre-operational trial proved that the subjective forecast was not too bad. So an expert system was developed to help fog forecasting on Frigg Field in the North Sea (60° N, 02° E). This system was named '4F' (Fog Forecasting on Frigg Field) (Tremant and Roland 1988) and the object of '4F' is to forecast fog for a maximum period of 24 hours using information sent by 'SHIP' messages on the GTS and the detailed analysis maps produced by the various European Weather Centres.

We use the PDIS 'M1' which operates with an IBM/PC compatible computer. The rules are written in PROLOG.

Principle of reasoning followed by the system

It is very important to note that '4F' system was intended for advection fog forecasting on Frigg Field (more than 90% of fog on Frigg Field is advection fog). This system does not forecast radiation fog on Frigg Field but it does take the evolution of such fog into account.

As far as advection fog is concerned, the logistics consists of following its movements in the North Atlantic Ocean. It is also necessary to check that meteorological conditions will not bring about its disappearance in the next 24 hours. It was also checked that there were no 'exceptional' meteorological conditions, and the extent of fog was determined with the help of meteorological data coming from around Frigg Field.

Definitions of areas of study

The most likely movements of perturbations forming off the coast of Newfoundland were considered in order to define three areas of study.

Firstly there was Frigg Field, the subject of the study.

The second area considered, called a sub-synoptic area is defined by the latitudes, 65° and 50° N, and the longitudes, 10° W and 10° E. This area is situated around Frigg Field. The fact that it extends to the north of the English Channel enables any depressions coming from the south to be taken into account, a phenomenon which happens especially in winter.

Finally an interesting area is defined which is called the synoptic area because it allows a picture of almost the whole of the North Atlantic Ocean. It covers from 45° to 70° N and 10° to 45° W. It is in this area that the movements of perturbations were followed.

Reasoning with uncertainty

The expert knowledge being represented includes a factor of uncertainty which has been taken into account in the representation adopted. For this we use a measure of confidence in the forecast and work with four values of certainty. Fog can be 'improbable', 'possible', 'probable' or 'certain' according to specified conditions attached to temperature, atmospheric pressure, and wind speed and direction.

Results obtained

To test our expert system, observations from meteorological charts from previous years were used. These enabled us to be free from mistakes made by the operator. When the system asks the operator for a forecast, the real value taken from the chart is used. Only the reasoning principle was tested, so eventual errors of forecasting are totally attributable to the system. The first results of the '4F' system were very encouraging, as shown in the contingency table below. This expert system was then used in 'real time' for 4 months and seemed to work correctly. However, it is illusory to think that it is possible to forecast all the fogs and it is necessary to remember that, in certain cases, it is as difficult to forecast 'no fog' as it is to forecast 'fog'.

	No fog	correct forecast of no fog	non-detection
F O R E C A S T S	No fog	correct forecast of no fog 110	non-detection 1
	Fog	false alert 3	correct forecast of fog 9

4. General conclusion

Many numerical models of fog forecasting (generally on land but also over sea) have been actually studied, but a better knowledge of the droplet spectrum, liquid water content and exchanges due to turbulent transport, seems to be necessary to obtain good forecasts of fog.

With statistical models, another problem is encountered — the lack of data over the oceans.

The information which can be extracted from the satellite images is expected to have considerable potential in fog forecasting.

Hence it is recommended that:

'Automatic visibility recorders are installed on ocean-going military and civilian passenger/cargo ships. This will place visibility observations on a more objective basis and lead to improved methods of forecasting visibility, as well as verifying such forecasts'.

Expert systems seem to be the ideal tool to forecast fogs, and more especially coastal fogs. It is very easy, for instance, to introduce rules which take into account the topography of the location for which the fog forecast is prepared.

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Improved values of 1-hour M5 rainfalls for the United Kingdom

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Summary

Previously existing data sets of annual maximum 1-hour duration rainfalls at locations in the United Kingdom have been enlarged with additional observations. This has enabled improved station values of the exceedance rainfall amount with a 5-year return period to be calculated and values for additional stations to be obtained; these are compared with presently used values dating from the early 1970s. The values for south-east England appear to show the influence of summer storms moving north-westwards from France.

1. Introduction

In 1975 the Flood Studies Report (NERC 1975) was published. The report, referred to as FSR, contains recommended values for the rainfall amount which has a specified average interval (return period) between exceedances, as a function of duration and location in the United Kingdom. These exceedance amounts are denoted by the abbreviation used in the FSR — 'duration M return period' values — where the return period is in years. The analysis of data leading to these results was carried out in the Meteorological Office and the methods used are described in the FSR. The data were observations of annual maximum rainfalls for a variety of durations extracted from original autographic records, manuscript tabulations and computer data sets of observations from daily-read storage rain-gauges and tilting-siphon recording rain-gauges, made at many stations in the United Kingdom. For sub-daily durations observations from just over 100 stations were available mainly covering the period from 1950, not long after many new Meteorological Office observing stations opened, to 1970 when the FSR data analysis started.

Because of the wide separation of these sub-daily stations it was not possible to produce an adequately detailed map of 1-hour (or 60-minute) M5 rainfall by simply contouring to station values (the small distinction between 60-minute and 1-hour duration rainfalls, unimportant at present, is explained later). Instead a method was used in which the few observed values of 1-hour M5 rainfall were related by regression equations to two parameters assumed to be associated with the size of extreme short duration rainfalls; these were the average number of days per year with thunder reported, and a complicated function of the occurrence of high humidities. The equations enabled an apparently more detailed map of 1-hour M5 rainfall over the United Kingdom to be produced. It was not stated in the FSR how well the regression equations fitted the data so that it is not possible to judge just how much of the detail in the map is correct; it is demonstrated later that the map does not appear to reproduce all the original FSR station values.

The FSR contains a copy of this map for occasional use but the map has also been digitized so that a spatially interpolated 1-hour M5 rainfall for a specified location can be extracted rapidly by computer. These values, produced by the 'ITED' computer program (Keers and Wescott 1977) are still used frequently by the Meteorological Office Advisory Services Branch after 11 years to answer enquiries in a wide range of applications.

In 1987 a further analysis of 1-hour annual maximum rainfalls was started. More data than were available in the early 1970s have been accumulated by extending station records forward to 1986 and backwards to the start of the observations, and data from additional stations have been found. This has enabled improved values of exceedance amounts to be obtained for a range of return periods but in this paper a description is given of results for 5-year return period values only. These are of particular relevance since they are frequently used by hydrologists and engineers in the design of drainage structures for urban catchments which are often sensitive to flooding from intense rainfalls of about 1 hour's duration. The aim of the work is to investigate whether there is any evidence which would suggest that the FSR recommendations require amendment or can be improved.

2. Estimation of 1-hour M5 rainfalls

In the FSR it is stated that the geometric mean of the annual maxima for a station in the upper half of their arrangement in ascending order of magnitude is an accurate estimate of the exceedance amount for a return period T which is approximately 5 years (strictly 4.45 years). The estimate for a T of exactly 5 years, M5, can be obtained by adding a small correction $+0.11\,\alpha$ where α is the slope of exceedance amount plotted against y, the reduced variate $= -\ln[\ln\{T/(T-1)\}]$. The exceedance amounts for other return periods, required to estimate α, are given by further functions of the ordered annual maxima as specified in the FSR. Typically α is $+5.0$ mm and so the correction is approximately 0.6 mm

or 3% to 6% of M5 which varies from about 20 mm in southern England to 10 mm in north-west Scotland.

This method is used in the work described here and in the FSR to estimate the 1-hour M5 rainfalls except that in the FSR it was not stated explicitly how the correction was made.

The standard error of the M5 estimate is given by s.e. $= 1.8 \times \alpha \times n^{-\frac{1}{2}}$ where n is the number of annual maxima used. The standard error decreases with n, i.e. the longer the record the more accurate the estimate is likely to be.

A detailed record of rainfall at a station can be analysed to produce annual maxima of either 60-minute rainfalls which can start at any time or, more usually nowadays, 1-hour rainfalls which are constrained to start on GMT hours. A 60-minute period can be located freely to contain the absolute largest rainfall in such a period during a year. This amount is as large or larger than the annual maximum for 60-minute periods which start on GMT hours because these periods cannot be located freely. As a consequence 60-minute M5 values are larger on average than 1-hour M5 values, by a factor of 1.15 as quoted in the FSR. Therefore, where necessary, 60-minute M5 values are multiplied by 0.87 to give corresponding estimates for 1-hour M5 rainfalls. All results in this paper are for 1-hour duration.

3. Sources of data

The following sources of annual maximum rainfalls are used here.

(a) The original values in manuscript for 112 stations, mainly for the period 1951–70 and extracted in the Meteorological Office for the preparation of the FSR. The maxima were for 60-minute rainfalls from 33 stations and 1-hour rainfalls from the remaining stations.

(b) Further tabulations of hourly rainfalls stored in the Meteorological Office's data archives at Bracknell, Edinburgh and Belfast have been scrutinized to extend many of the records in section 3(a) backwards to the start of observations and forward to 1979. Annual maxima have also been extracted for additional stations whose tabulations were not available at the time of the FSR analysis. Since 1980, hourly totals have been transferred routinely to computer data sets and the annual maxima have been extracted from these.

A computer data set of all these annual maxima has been created with provision for updating. It is believed that this now contains most of the reliable 1-hour or 60-minute annual maximum rainfalls available from sources within the Meteorological Office Archives. Some stations have values missing for occasional years but if these are randomly distributed through the length of records this does not result in bias errors in the M5 values. In this work, record length is the number, n, of the annual maxima in a station's record. For some stations only recently commencing observations the record lengths are short but their maxima have been included in the data set in anticipation of their continued operation giving data for future use.

Fig. 1 shows the number of stations with the indicated record length as used in the FSR, and in this work. The number of annual maxima are 2284 and 4532 and the number of stations 112 and 234 respectively, about doubled in both cases. The data from new stations are mainly confined to England and Northern Ireland while the addition to Scottish and Welsh data is mostly in increased record lengths. Unfortunately the addition of new data does little to improve the lack of observations from high altitude stations, Ben Nevis (National Grid
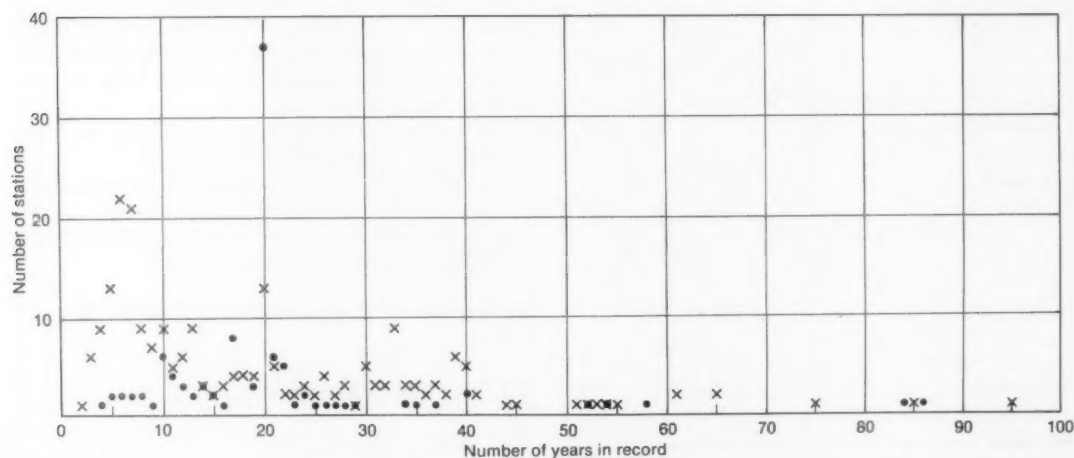

Figure 1. Statistics of station record lengths used in the FSR (dots) and in this paper (crosses), showing the numbers of stations having the specified number of annual maximum 1-hour (or 60-minute) rainfalls in their record.

Reference NN 167713) at 1343 m still being the only station with an altitude greater than 400 m. The stations are distributed over the whole of the United Kingdom but concentrated in south-east England as shown in Fig. 2 in which those with record lengths of 20 years or greater, i.e. at least four times the return period, are shown by the larger dots.

4. Variation of extreme 1-hour rainfalls and M5 values with time

In the FSR, 1-hour M5 values were presented as being generally applicable to a period of few decades up to 1970 without any consideration of whether there were changes during that period in the 'climate' of extreme rainfalls. This was mainly because record lengths for sub-daily rainfalls were inadequate. The extended data
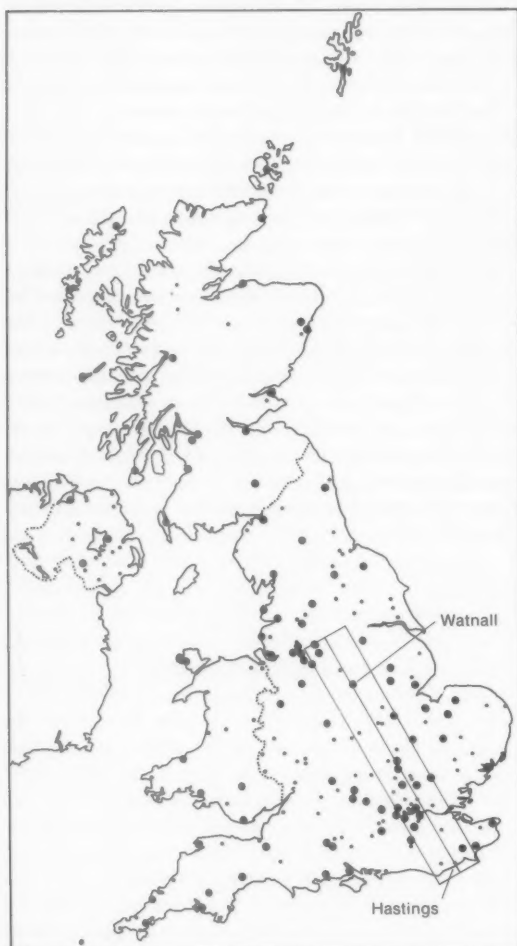
Figure 2. Location of stations whose annual maximum rainfalls have been used in this study. The larger dots indicate those stations with record lengths of 20 years or more. The rectangle, of width 60 km, along a line from Hastings (East Sussex) to Watnall (Nottinghamshire), contains the stations whose 1-hour M5 rainfalls are plotted in Fig. 4.

set of annual maximum 1-hour rainfalls now available has enabled an investigation of changes in the size of extreme rainfalls and 1-hour M5 values to be made.

May and Hitch (1989) have demonstrated that over the period from 1881 to 1986 these annual maximum rainfalls contain roughly sine-wave variations of period 7, 11, 20 and 50 years with amplitudes of 7%, 10%, 5% and 7%. They have also suggested that these variations occur synchronously over most of the United Kingdom (but at any specific station they are hidden by the larger natural random year-to-year variation of annual maxima) and affect all large rainfalls, not only the maxima.

Since about 1940 the amplitude of the 20- and 50-year period waves have reduced almost to extinction, but the 7- and 11-year period waves have maintained their size over the whole of the 106-year interval. The latter waves appear to be related to the 11-year periodicity of solar activity but their combination has maxima at alternate intervals of 9 and 13 years, instead of 11 years. On the basis of past behaviour, the next maxima of rainfalls are expected to occur in 1990 and 2003, and minima in 1996 and 2007, with magnitudes of about 10% greater and 10% less than the overall average since 1940.

In effect M5 values have a variability which is influenced by this periodicity of extreme rainfalls in both magnitude and phase. Depending upon the length and epoch of a record, an M5 value may contain some influence of the 7-, 11-, 20- or 50-year period variation. In this work all M5 values were corrected to equivalent values appropriate to the period since 1940 though of course they are still inaccurate to some extent because of the finite record lengths used. All of these corrections were smaller than ±4% and most were zero.

5. The 1-hour M5 values which are compared

The following values are investigated:
(a) the original 'FSR' values, which were derived in the preparation of the FSR as described in section 2 (apart from the unknown correction) using the data described in section 3(a),
(b) values generated using the 'ITED' program which was based on the FSR data, and
(c) 'MH' (May-Hitch) values, along with their standard errors calculated from the longer records from more stations described in section 3(b) using the methods described in section 2.

6. Results of comparisons of 1-hour M5 values

6.1 MH and FSR values

6.1.1 With identical maxima

This comparison is made to determine the component of (MH−FSR) differences arising from the way the small correction described in section 2 is applied; it is

made for the sample of 38 stations (well distributed over the United Kingdom) for which the MH and FSR M5 values are calculated using the identical sequence of annual maxima. The small interquartile range, 0.2 mm, confirms that the differences are nearly constant with a median value of +0.4 mm, which is very small compared with other differences described later and with the range of M5 over the United Kingdom.

In effect, the methods used to calculate the MH and FSR values give nearly identical results.

6.1.2 Approximately doubling the record length

It is useful to investigate changes in M5 values arising from changes in record length. There are 37 stations used to calculate the FSR values with original record lengths which have been approximately doubled prior to calculating the MH values, typically from about 19 to 38 years. The M5 values are either increased or decreased by increasing the record length, which results in an increased interquartile range of (MH−FSR) of 1.5 mm with a median value of +0.6 mm, of which 0.2 mm and +0.4 mm respectively can be attributed to the (MH−FSR) differences described in the previous section. This suggests that the balance of 1.3 mm in the range and +0.2 mm in the median is the increase resulting from doubling of record length, and again these are small compared with the range of M5 values. This size of increase of record length is unlikely to change the broad-scale picture of the variations of M5 over the United Kingdom. It does not mean though that it is pointless continuing making measurements to increase record lengths and hence accuracy; the consequent improvement in accuracy of the M5 values enables interesting and significant smaller-scale detail to be resolved as demonstrated in the next section.

6.2 MH and ITED values

The main purpose of the work described in this paper is to compare the new MH values with the established ITED values.

Fig. 3 is a map of contours of the percentage difference between MH and ITED values defined by {(MH−ITED)/MH} × 100%. The station values are not shown for reasons of clarity. The positions of the contours in Fig. 3 were estimated by eye taking into account the standard error of each MH value and giving a greater weight to the values with small error; they are drawn over some sea areas only as a visual guide. In Scotland (especially), Wales and the south-west region the stations are still widely separated in spite of the increased numbers and this leads to an inevitable lack of detail in the contoured fields in these areas. In Northern Ireland there is more implied complexity of the field but it is based mainly on station records of less than fifteen years' duration (only three stations have longer records — Armagh, Aldergrove and Ballykelly with $n = 85$, 61 and 24 years). The densest congregation of stations is in the London and Manchester areas.

Over the United Kingdom as a whole the percentage difference ranges from about −30% (MH less than ITED) to +20%. At first sight there appears to be no reason for the particular shape or position of the contours — for instance they are not obviously related to large-scale areas of high ground which is the case for other aspects of rainfall such as the annual average. However, the denser observations in south-east England depict an interesting pattern of alternate elongated areas of positive and negative differences roughly transverse to a line drawn from Hastings to Watnall and beyond, as indicated in Fig. 2. This undulating pattern could be caused by similar variations in the MH or the ITED
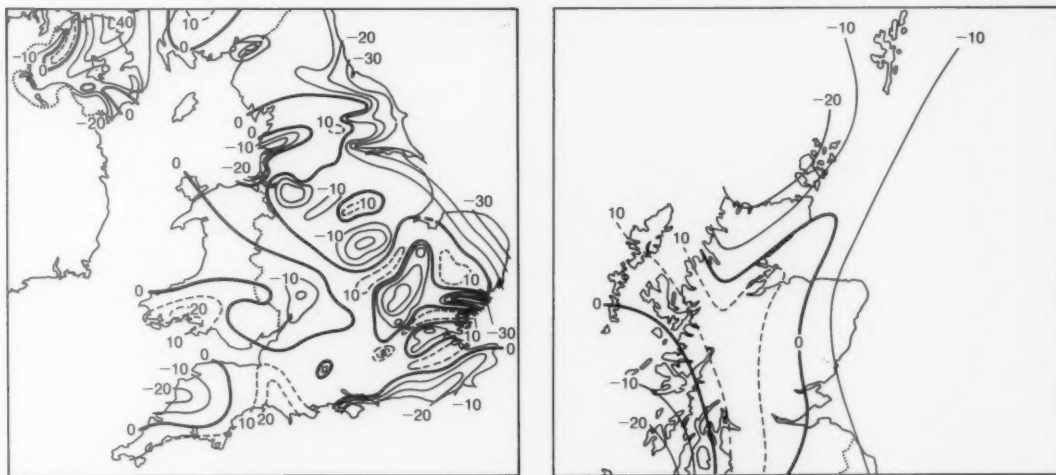

Figure 3. Isopleths of {(MH−ITED)/MH} × 100%, where MH values are 1-hour rainfalls described in this article and ITED values are based on the digitized version of the FSR map. Isopleths are at 10% intervals, with positive values being dashed and negative being full lines; the zero isopleths are the bold lines. See text for explanation of terms. The diagram is split for convenience.

values, or both. In Fig. 4(b) are plotted the MH values of 1-hour M5 with their standard error bars for all stations within 30 km either side of the Hastings–Watnall line against their distance along the line north-westwards from an arbitrary reference point off the coast as shown in Fig. 2. These values show a clear undulation whereas the ITED values for the same stations, as shown in Fig. 4(a) show hardly any variation at all. For comparison the smaller number of original FSR values are shown in both Figs 4(a) and 4(b). They agree well with the MH values (with the exception of one station) which is to be expected from the results of the previous comparisons. The FSR values plotted in Fig. 4(a) suggest the presence of the undulation as is also the case in the FSR map, but not with the clarity of the MH values. In Fig. 4(a) the ITED values do not even reproduce the small amount of structure implied by the FSR values but are a very smoothed version of them. This departure between FSR and ITED co-located values is extensive over the United Kingdom — for a widespread sample of 88 stations the difference (FSR–ITED) has an interquartile range of 2.0 mm and a median of −0.6 mm. These values increase to 3.7 mm and −0.9 mm for (MH−ITED) differences for 48 stations which were not used in the construction of the FSR map; taking into account the (MH−FSR) contribution, the equivalent (FSR−ITED) differences for these independent stations have a range and median of about 3.5 mm and −1.3 mm. These results suggest

that the ITED values depict only the large-scale features of the variation of 1-hour M5 values over the United Kingdom, probably not as much as is implied by even the original FSR station values, and they do not even reproduce those very closely, although their standard errors are about 2.5 mm on average.

Although some of the MH values have large standard errors the overall consistency with which they show the undulation in Figs 3 and 4(b) gives confidence in its reality.

The Hastings–Watnall line is of interest because it cuts across successive areas of high ground — the Sussex Weald, North Downs, Chiltern Hills, Northamptonshire Weald and finally the Peak District, as shown schematically in Fig. 4(c). The spatial wavelength of the undulations in 1-hour M5 rainfall is close to that of the underlying ground height. It is not possible to say whether the maxima of 1-hour M5 of about 20 mm and the minima of about 14 mm, are more closely co-located with the maxima, minima or intermediate slopes of the ground profile. Certainly a strong possibility is that the maxima of 1-hour M5 are co-located with the south-east facing ground slopes as indicated by the lines in Fig. 4, and the undulating pattern in Fig. 3 gives the impression of spreading from the south coast. This suggests that we are seeing the effects of heavy rainfalls produced by orographic uplifting associated with summer thunderstorms which are observed to develop over the French mainland, cross the English Channel perhaps favouring
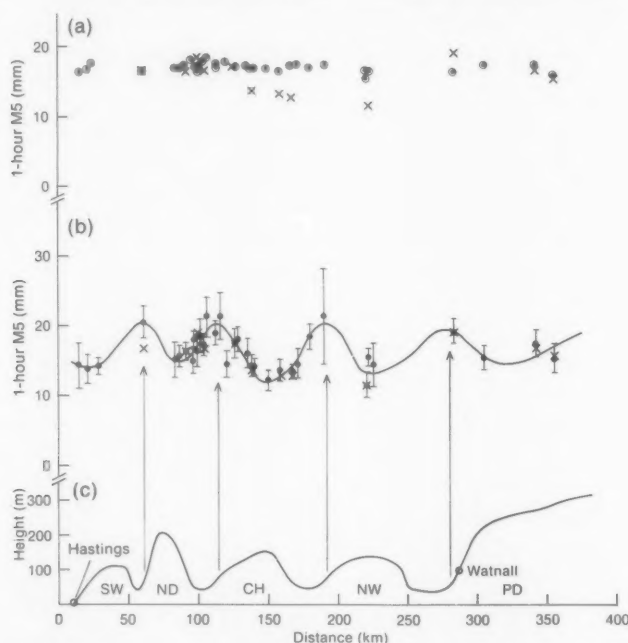

Figure 4. Variation in (a) ITED (dots) and FSR (crosses), (b) MH (dots with standard error bars) and FSR (crosses) station values of 1-hour M5 rainfall as a function of distance along the Hastings–Watnall line (terms as in Fig. 3), from all stations in the rectangle in Fig. 2, and (c) is a schematic cross-section of ground height along the Hastings–Watnall line, where SW = Sussex Weald, ND = North Downs, CH = Chiltern Hills, NW = Northamptonshire Weald and PD = Peak District.

the narrowest crossing and then travelling north-westwards well into the Midlands; this behaviour is well known to forecasters but is not well documented. It should be noted that, according to Prichard (1976), the major thunderstorm regions in the United Kingdom are the Pennine Hills, particularly around the Peak District and the east Midlands especially from Nottingham to the western suburbs of London, an area roughly coinciding with the rectangle in Fig. 2.

7. Variation of occurrence of annual maximum rainfalls during the year

During the extraction of the annual maximum rainfalls the month in which they occurred was noted and for each station an index, I, was calculated which is the percentage of years in which the maxima fell in the 'summer' months April–September. An index of 100% indicates all maxima occurring in summer and 50% means that they are distributed more evenly throughout

the year. Fig. 5 shows a map of I based on stations with record lengths of 20 or more years. Apart from areas of south-west England and Wales, and north-west Scotland, with $I \approx 60$–70%, the maximum rainfalls show a strong tendency towards summer occurrence with $I \approx 90$–100% particularly in the area from south-east England through the Midlands to the Manchester area. Again in the south-east the undulating pattern in evident as in Fig. 3, though the position of its features are not obviously related to those of M5.

8. Conclusions

The new results reported here with their greater accuracy indicate that 1-hour M5 rainfall in south-east England (at least) has a more complicated structure than is indicated by the map in the FSR and its digitized version used in the ITED computer program. The FSR map probably oversmooths the original FSR station values on which it was based presumably because of the particular way in which climatological data were used to improve the map through regression techniques.

The larger number of station values of 1-hour M5 rainfall now available allows a more detailed map for south-east England to be drawn directly without the use of supplementary data. In this area the spatial variation of M5 appears to be related to high ground in a way which depends upon the local meteorology of summer storms. This suggests that it may be difficult to devise general regression schemes for interpolation between station values over the whole of the United Kingdom using conventional climatological or topographical data as in the FSR. It is not known whether the availability of more station values in other parts of the United Kingdom would reveal a more complicated structure of 1-hour M5 rainfall determined by their local storm meteorology. It seems that there may be a role here for radar observations of rain with their dense coverage in time and space for determining the local meteorology of the occurrence of extreme falls in different areas, which could then be used to infer small-scale structure within the accurate M5 values from gauge observations.

Acknowledgement

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Figure 5. Isopleths of I, the percentage of years in which the annual maximum 1-hour rainfall occurs in the 'summer' months April–September.

Local forecasting of a small-scale synoptic event over the Isle of Man on 18 November 1986

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Summary

The rainfall distribution and low-level winds associated with a warm front wave which passed over the south and east of the Isle of Man on 18 November 1986 are analysed, illustrating some of the problems associated with forecasting for an island smaller than the grid size of a fine-mesh numerical model (Meteorological Office 1986 version).

1. Introduction

A warm front wave moved eastwards across the Irish Sea during the evening of 18 November 1986, passing over the south and east of the Isle of Man, producing heavy rainfall and local flooding. Flooding is not common on this rugged island, but was particularly severe in and near the village of Laxey, which lies at the seaward conjunction of two deep river valleys on the eastern side of the island (Fig. 1).

The climatological rainfall distribution over the island virtually follows the orographic contours, with over 125% more rainfall on the highest ground than on the north and south coastal extremities. However on this occasion the rainfall distribution was markedly different (Fig. 2), with most of the rain falling on the south-eastern slopes of the south-west to north-east ridge of high ground which forms the 'backbone' of the
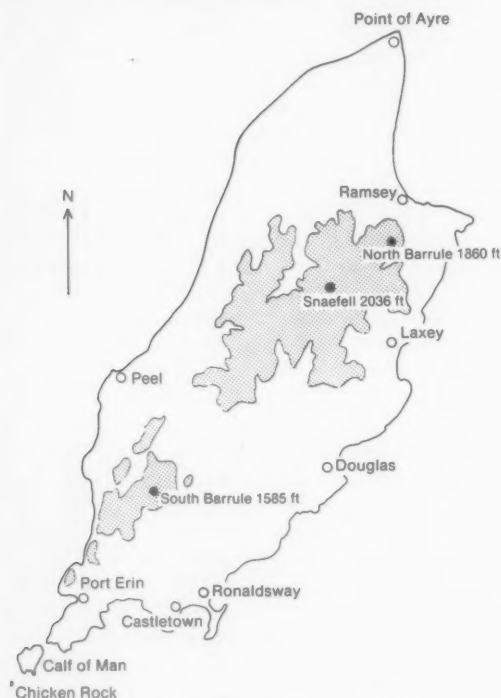
Figure 1. Map of the Isle of Man (situated in the Irish Sea) showing location of places mentioned in the text. The stippled area denotes land above 750 feet.
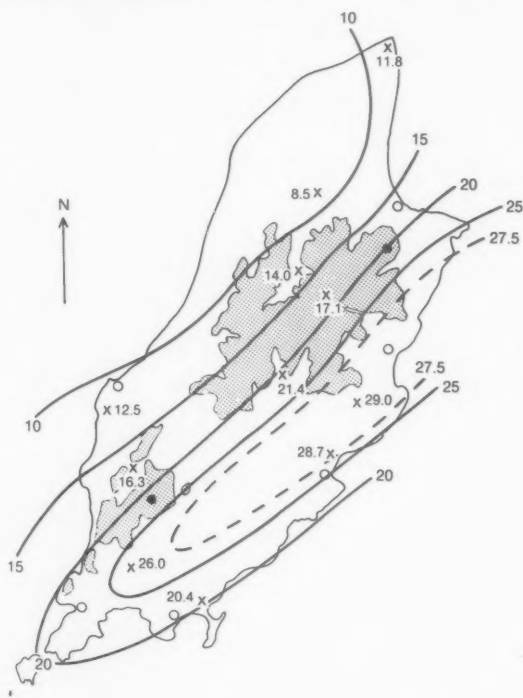

Figure 2. Contours of rainfall (mm) over the Isle of Man between 0900 GMT on 18 November and 0900 GMT on 19 November 1986. Crosses with small figures show location of rain-gauges and measured amounts (mm). High ground stippled as in Fig. 1.

* Mr McGain died during the preparation of this article, which was completed by Dr A. Hisscott of the same department.

island. The highest daily totals (0900 GMT on 18 November to 0900 GMT on 19 November) approached 30 mm (most of which fell between 1800 and 2200 GMT) and occurred in the Douglas-Laxey area.

Ronaldsway is a forecasting office with aviation and public service commitments. Forecasters rely heavily on surface synoptic charts and numerical model forecast products broadcast from Bracknell by landline facsimile. This event illustrated some particular difficulties in forecasting for an island which is smaller than the grid length of the fine-mesh model (Meteorological Office 1986 version) and not explicitly represented in the model topography. The teleprinter broadcast of radar rainfall information from the UK weather radar network proved useful, but satellite images (received locally from Meteosat using Feedback WSR 513/5 equipment) were of little value in this instance because the whole weather system was shielded by a thick cirrus layer.

2. Synoptic details

Fig. 3 shows the path of the centre of low pressure associated with the warm front wave from the west coast of Ireland at 1800 GMT on 18 November 1986 across the Irish Sea and northern England to reach the North Sea by 0200 GMT on 19 November. The central pressure slowly filled during that time from 989 mb to 990 mb as it passed close to Ronaldsway at 2200 GMT, then to 992 mb by the time it reached the North Sea. The leading edge of the warm air at the surface is also indicated at 2-hour intervals. The warm air progressed
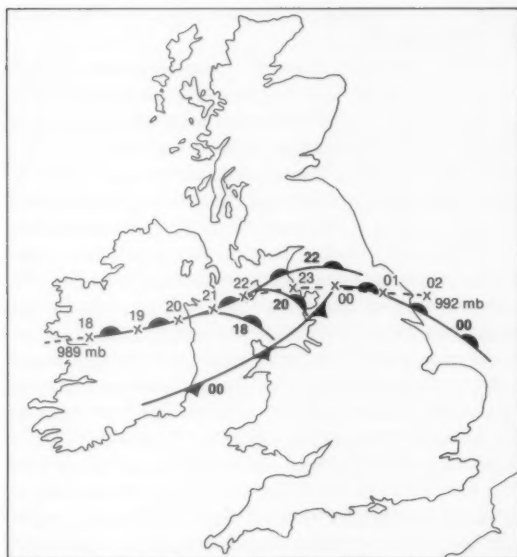

Figure 3. Track of low pressure centre as it crossed the British Isles. Crosses show position of centre from 1800 GMT on 18 November to 0200 GMT on 19 November 1986 with values of central pressure at those times. Also indicated are the positions of the surface warm front at 2-hour intervals (times shown in bold) and the surface cold front at 0000 GMT on 19 November 1986.

north-eastwards from southern Ireland at 1800 GMT up the east side of the Isle of Man during the evening to reach its most northerly extent (Ramsey–Cumbria) by 2200 GMT. It appears that the surface front became quasi-stationary over the east side of the Isle of Man, with the transition from a northward moving warm front to a south-eastward push of cold air occurring probably near Laxey (perhaps influenced by the orographic uplift and convergence provided by the island).

An accurate location of the warm front was provided by an executive turbo-prop aircraft equipped with instrumentation to display instantaneous wind speed and direction, on approach to runway '09' at Ronaldsway. At 1900 GMT the pilot reported a wind of 220° 54 kn at 1000 ft over Chicken Rock (in the warm air) and flew through the front to reach Ronaldsway some 14 km east-north-east at 1907 GMT where the surface wind was 080° 12 kn. The pilot reported 'significant low-level wind shear on approach'!

The warm air reached Snaefell, the highest peak on the island at 2036 ft, at around 2000 GMT when the surface wind changed from easterly at 30 kn to south-westerly at 12 kn by 2015 GMT. The surface front did not reach as far north as Point of Ayre, where the surface wind remained between east and north-east throughout the evening and the dew-point did not rise above 8 °C (compared with 10 °C characteristic of the warm air). Subjective reports of surface wind suggest that the low centre passed north of Ronaldsway but south-east of the ridge of high ground at South Barrule (1585 ft). The largest rainfall accumulations occurred along the surface front as it lay over the eastern flank of the Isle of Man. The largest recorded total, near Laxey, was probably due to the front becoming quasi-stationary here as the cold air began to push south-eastwards. Onshore low-level winds may have also contributed through orographic enhancement.

3. Local forecasts

Ronaldsway is a small forecasting office. Most forecasts are based on surface chart analysis (assisted by satellite and radar information) and the fine-mesh and coarse-mesh numerical products broadcast from Bracknell. The fine-mesh data are normally particularly useful. The mean-sea-level pressure fields assist in estimating surface winds at the airfield and over the northern Irish Sea. The 850 mb wet-bulb potential temperature (θ_w) fields, in conjunction with sea surface temperatures measured daily at Port Erin by the Marine Biological Station, are useful in predicting low cloud and coastal fog. The 6-hour accumulated rainfall totals at the closest fine-mesh grid-point (east of the island, highlighted in Fig. 4) are usually a helpful guide to precipitation amounts and intensity expected over the island.

The T+24 hr fine-mesh forecast frames for 0000 GMT on 19 November 1986 (based on analysis of data from the previous midnight) are shown in Fig. 4(a).
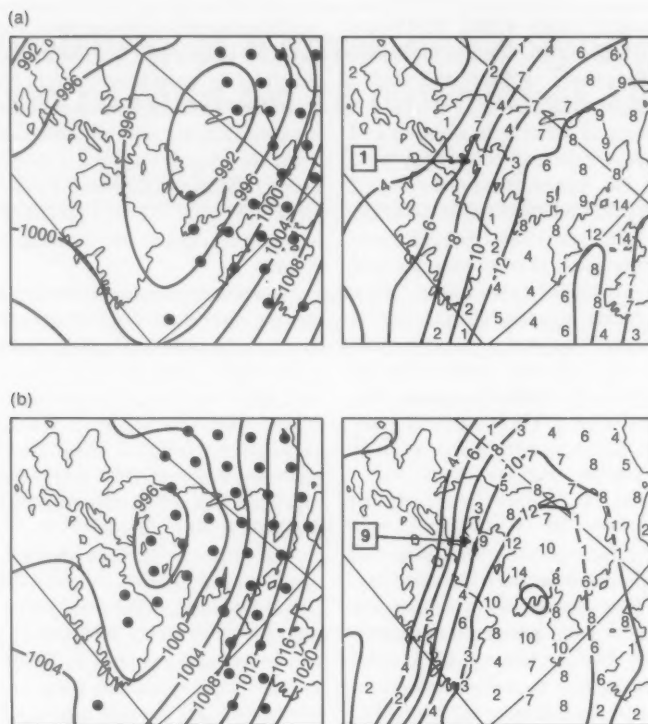
Figure 4. Fine-mesh model forecasts of mean-sea-level pressure (mb) and instantaneous rainfall (dots show 0.5–4.0 mm h⁻¹) on the left, and 850 mb θ_w contours (°C) and 6-hour (to verification time) accumulated rainfall totals (mm) on the right, for (a) 24-hour forecast, and (b) 12-hour forecast, both verifying at 0000 GMT 19 November 1986. The highlighted rainfall accumulation forecast is for the grid point nearest to the Isle of Man.

Similar forecast frames for the same time but a T+12 hr forecast from midday data on 18 November are shown in Fig. 4(b). The pressure pattern for both forecasts is quite good, with a low centre crossing the Irish Sea during the evening, although the timing of the earlier forecast proved to be too fast and that of the later forecast too slow, and the warm-sector winds were significantly stronger in the latter. The 850 mb θ_w pattern of the T+24 hr forecast showed a θ_w gradient across southern Ireland, North Wales and northern England, whereas the later T+12 hr forecast showed a much tighter band of θ_w gradient further north across the Isle of Man which correlated well with the observed frontal behaviour.

The earlier forecast predicted a midday to midnight 12 hr rainfall accumulation of 3 mm at the grid point closest to the island. Morning forecasts issued from Ronaldsway, based on this information, did not mention heavy rain explicitly. The later fine-mesh forecast predicted 13 mm at this point during the same period, and afternoon forecasts disseminated by Ronaldsway mentioned periods of heavy rain, and a warning was issued to the local authority (based on a criterion of 10 mm accumulation). Both numerical forecast runs predicted the largest rainfall accumulations further south in the warm sector, away from the front.

4. Discussion

Analysis of observations from around the Isle of Man on the evening of 18 November 1986 showed that the heaviest rainfall occurred close to the surface front and that there was significant wind shear associated with this synoptic feature. Neither of these phenomena could be easily inferred from the available fine-mesh numerical forecast products. Although the large-scale advice from the model is basically very good, forecasters must beware of the model tendency to average out quantities over the scale of one or two grid lengths, shifting the emphasis away from the air-mass discontinuity whereas in the real atmosphere many of the interesting features arise from the dynamics of the discontinuity. In this case, curving of the isobars to fit smoothly between grid points detracts from the detail of the observed wind shear. The occurrence of almost 30 mm of rainfall on one side of the island and less than 10 mm on the other is not far from the model prediction of 13 mm averaged over the area represented by one grid square. However, the model output would not lead forecasters to expect the heaviest rainfall along the surface front. Although most research today is done in terms of numerical models there is still a need for detailed synoptic analysis of interesting weather features.

Mechanisms of orographic precipitation*

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Summary

The mechanisms which are thought to produce orographic rainfall in various climate zones of the world are discussed.

1. Introduction

The effect of mountains on the hydrological cycle is most clearly seen on maps showing the correspondence between patterns of precipitation amount and terrain height. Examples are shown in Figs 1 and 2. This correspondence has been known in some geographical areas, and suspected in others, for many years, yet scientific research on the problem has proceeded slowly. The current understanding of orographic precipitation is reviewed in this article. More general discussions of the subject are given by Bonacina (1945), Browning (1978, 1980) and Smith (1979).

Orographic precipitation enhancement occurs in a wide variety of latitudes, climates and weather conditions, near terrain of differing size and shape. It appears almost certain that the enhancement mechanisms vary from region to region. Four basic mechanisms have so far been identified: smooth forced ascent, the Bergeron seeder-feeder cloud mechanism, diurnally forced convection and triggered convection by forced ascent or blocking.

2. Smooth forced ascent

A common aspect of orographic precipitation is that the enhancement occurs on the upwind side of a mountain range. In some climates this relationship is so reliable that the precipitation pattern around a mountain range can be used as a crude indicator of regional wind direction. In a recent study, Fjørtoft (personal communication) suggests that the rainfall at three stations in Norway can be used to classify the northern hemisphere circulation features into distinct flow types. Each distinct circulation type brings upslope conditions to the different stations in Norway. Such a correlation is remarkable considering that no details of the precipitation process (synoptic, mesoscale, or cloud physical) are considered.

The most often heard explanation for such observations is that smooth terrain-forced ascent will cool the air adiabatically, producing condensation and perhaps precipitation (Fig. 3(a)). Although this is the textbook

Figure 1. Mean annual precipitation in Norway during the period 1931–60 showing the enhancement near west-facing mountains. The stippled area receives more than 125 cm, while the annual global average precipitation is 88 cm.

Figure 2. As Fig. 1 but for the Indian south-west monsoon season.
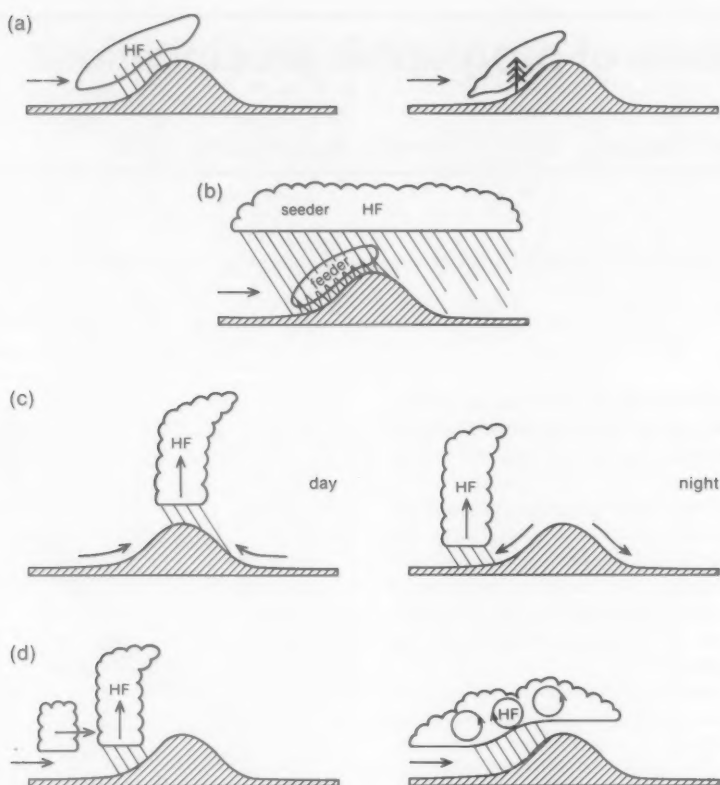
Figure 3. Four idealized mechanisms for orographic rain, (a) smooth forced ascent with hydrometeor formation or scavenging by foliage, (b) seeder-feeder, (c) diurnal convection and (d) triggering penetrative or shallow convection. The region of hydrometeor formation (HF) is shown.

explanation for orographic rain, it has a serious weakness. As pointed out by Bergeron (1960), if the mountain width and the wind speed are moderate, there is not sufficient time for hydrometeor formation; both the collision-coalescence mechanism and the ice-phase mechanism take time to work. Furthermore, supercooled water, which is needed for the ice-phase mechanism, may not be present in the low-level air forced up by terrain. As research on these problems has advanced over the last 20 years, it has become more and more possible that the 'textbook' mechanism may not be found anywhere on earth! Of course it is still a convenient way for beginning to teach students about the thermodynamics relating ascent and condensation.

One recently proposed location for the application of the smooth forced ascent model is the island of Hawaii. Data from the Hawaiian Warm Rain Project in 1985 suggest that very rapid hydrometeor formation is possible in ascending air upwind of the island (Cooper, personal communication). Perhaps salt crystals in the maritime air mass act as giant cloud condensation nucleii and accelerate the coilision-coalescence process. We must await a complete analysis of that data to rehabilitate the forced ascent model.

A modified version of smooth forced ascent is known to occur. Low-level cloud droplets generated by forced ascent can be directly removed from the air by impact on tree foliage. The resulting precipitation is called 'tree-drip'. This can be a primary mechanism of precipitation on windward slopes in the subtropical high pressure belt where the descending branch of the Hadley cell discourages cloud formation. The Canary Islands (latitude 28° N) experience this phenomena as does the coastal range of Queensland, Australia (near latitude 25° S).

Rejection of the smooth forced ascent mechanism implies that other factors are needed to explain orographic rain. This agrees with a most important observation; orographic precipitation, i.e. heavy rain on the windward slopes, is almost always accompanied by weaker precipitation over a larger region. Thus high terrain seems to enhance precipitation but not act as its sole cause.

3. The Bergeron seeder-feeder cloud mechanism

The difficulty in the rapid production of hydrometeors in low-level orographically lifted air was addressed by

Bergeron's suggestion of a two-cloud system of oro- graphic precipitation enhancement. An upper 'seeder' cloud is presumed to be precipitating with no influence from the terrain (Fig. 3(b)). This cloud is associated with ascent in a regional synoptic-scale disturbance. Its mid- troposphere position (and temperature) allows an ice- phase formation of hydrometeors. The precipitation from the regional seeder cloud is partly evaporated on the way to the earth's surface. This decreases the rainfall rate at the surface and serves to moisten the low-level air. When this air is locally lifted by the terrain, it reaches saturation quickly and a dense low-level cloud or fog is formed, i.e. the feeder cloud. The falling hydrometeors collect cloud droplets from this 'feeder cloud' and grow in size. Great droplet enlargement may lead to drop-splitting and multiplication. Even on small hills (height ≈ 100 m) significant rainfall enhance- ment may result.

The pure seeder-feeder mechanism is an idealization. In practice, the two clouds may be combined into one. Furthermore, the seeder cloud may be influenced by the terrain. A further description of the seeder-feeder mechanism can be found in papers by Bergeron (1960), Browning et al. (1974, 1975), Storebø (1976), Bader and Roach (1977), Passarelli and Boehme (1983) and Carruthers and Choularton (1983).

4. Diurnally forced convection

One of the most regular and predictable types of orographic rain occurs in warm season conditions over high mountains. The daily heating of the hillsides generates warm upslope winds which continue rising after reaching the mountain ridge-top and trigger deep convection (Fig. 3(c)). These clouds produce precipita- tion in the afternoon over the peaks or downwind if there is cloud drift. This behaviour is shown clearly in satellite movie-loops and is part of the daily cycle for people who work or live in the high mountain areas during the summer. The precipitation patterns on islands and mountainous coastlines throughout the tropics are dominated by this mechanism.

At night the thermally forced winds reverse, and low- level convergence may trigger convection some distance away from the mountains. On mountainous tropical islands this may produce a statistical night-time precipitation maximum near the coast or offshore. East of the Rocky Mountains, thunderstorms may build over the Great Plains at night.

Further discussion on the subject of diurnally forced convection over mountains is found in papers by Liu and Orville (1969), Kuo and Orville (1973), Astling (1984) and Banta (1984).

5. Triggered convection by forced ascent or blocking

In an attempt to understand how terrain can influence precipitation so strongly, it is often supposed that forced lifting can trigger some sort of instability which will then produce additional condensation and hydrometeor formation (Fig. 3(d)). Three possibilities have been mentioned:

(a) blocking and upstream lifting triggering deep penetrative convection, e.g. Smith and Lin (1983), Grossman and Durran (1984) and Smith (1985),

(b) blocking and upstream lifting triggering condi- tional instability in stratiform layers (e.g. Lee 1984), and

(c) blocking and differential advection causing fronts to overturn, triggering conditional instability in stratiform layers (e.g. Smith 1982).

These suggested mechanisms are rather difficult to verify for at least two reasons. First, if the environment is close to instability, there are likely to be disturbances and precipitation already in the area. This makes it difficult to isolate the effect of the mountain. Second, in interpreting surface rainfall amounts, the effect of low- level feeder cloud enhancement must be subtracted out. The question then is whether the seeder cloud is influenced by the terrain. Observationally this is best studied by direct aircraft measurements (Marwitz 1974, 1980) or radar (Browning et al. 1974).

As an example of these problems, consider the Western Ghats (Fig. 2) on the west coast of India. The undisputed facts are these:

(a) during the south-west monsoon, the rainfall is much greater on the coast and the windward slopes than east of the mountains, and

(b) the rainfall is associated with deep convection.

One could postulate that an upstream blocking effect of the mountains could trigger convection in the approaching south-westerly air current, but verification of this idea is difficult as the statistics and synoptic meteorology of cloud clusters in the Arabian Sea are poorly understood, and the upstream effect of the Ghats is difficult to estimate.

An alternative solution to the Western Ghats problem is pictured in Fig. 4. Naturally occurring convection over the sea and the coastline during disturbed or unstable conditions will be cut off at the mountain ridge due to an air-mass modification effect. Low-level air will be scavenged of its water by drops falling from a seeder cloud above. As the air descends beyond the mountain crest it is dry and cannot restore its water vapour by evaporation from the sea. Without the low-level moisture, convective precipitation is suppressed.
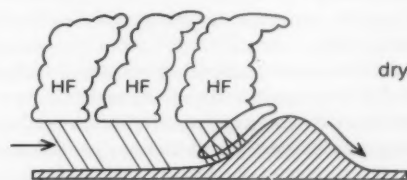

Figure 4. Orographic control of precipitation by an air-mass modification effect. The region of hydrometeor formation (HF) is shown.

6. Climate type and orographic rain

The relative importance of the mechanisms mentioned above is not known. The possibility of finding these mechanisms in each climate zone might be roughly as follows:

Tropics/monsoon

Diurnal convection	certain
Upstream triggering of convection	possible
Orographic air-mass transformation	possible
Seeder-feeder	likely

Subtropics

Smooth forced ascent	possible
Tree-drip	certain

Mid latitudes

Seeder-feeder	certain
Upstream triggering of stratiform convection (winter)	possible
Diurnal convection (summer)	certain

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Notes and news

Monthly and annual totals of rainfall 1985, and 1986, for the United Kingdom

These volumes are, in effect, the 126th and 127th in a series containing tabulations of rainfalls for UK stations, and commentaries on rainfall, which first appeared in 1860.

Dr G.J. Symons produced the first volume of *British Rainfall* for the organization of the same name as a hard-cover book of small-page format (127 mm × 203 mm) containing yearly total rainfall data for about 500 stations in the United Kingdom (then including all Ireland) for 1860. By 1884 the volume had expanded to include monthly totals for 233 stations and yearly totals for 2000 stations plus articles of interest to rainfall observers. In 1919 the functions of the British Rainfall Organization were taken over by the Meteorological Office which produced the last volume in this page size in 1960 by which time it contained monthly and yearly totals for 414 and 6000 stations respectively. In 1961 the page size was enlarged to 203 mm × 305 mm and the contents were standardized for the next few years to include tabulated rainfall totals, wet and dry spells and evaporation, and maps of annual total. In 1969 the volume appeared only in paper-back form with only the general table of monthly and annual rainfall.

The latest changes starting with the 1985 edition involve content and printing style. The contents are now:

(a) Explanatory section.

(b) Description of the rainfall station numbering system.

(c) A summary of rainfall for the whole year plus details of extreme falls.

(d) Maps of annual rainfall totals (amount, and percentage of the 1941–70 average).

(e) Maps of monthly rainfall as a percentage of the 1941–70 average and summaries of features of the rainfalls in the month.

(f) Monthly, seasonal and annual areal rainfalls for various regions of the United Kingdom.

(g) Tables of monthly and annual totals for about 4500 stations (currently), and the largest daily total for approximately 65% of this number, which form the bulk of the volume.

The opportunity has also been taken to use a more legible type-face than that used previously which makes all parts of the text easier to read. This is particularly true of the comprehensive tabulations of monthly and annual totals which, by necessity, have to be printed small to avoid producing a volume which is too bulky. The cover, too, has been redesigned to incorporate the Meteorological Office's commercial logo and drawings of suitable 'watery' themes.

To the keen student of rainfall in the United Kingdom this volume, like its predecesors, contains the expected wealth of detail, but now more attractively presented. The maps of monthly rainfall and the accompanying commentaries are particularly useful additions.

The 5th IAMAP Scientific Assembly, Reading, 31 July to 11 August 1989

1. History of IAMAP

In 1919 the International Union of Geodesy and Geophysics (IUGG) was formed, embodying a Meteorological Section which brought together already-existing bodies (such as the International Radiation Commission) formerly part of the International Meteorological Organization. The Meteorology Section of IUGG became the International Association of Meteorology in 1930 but in 1957 it took over interests in Atmospheric Physics as well, resulting in the International Association of Meteorology and Atmospheric Physics (IAMAP) as it exists today.

The World Meteorological Organization (WMO) assumed responsibility for operational matters leaving the non-governmental IAMAP to represent the interest of researchers from universities and laboratories (but not exclusively).

2. IAMAP/WMO relationships

IAMAP profits from the guaranteed continuity provided by WMO in matters of observing systems and their improvement, the maintenance of data archives and the development of atmospheric circulation and climate models. On the other hand WMO benefits through the intellectual stimulation and research activities initiated by IAMAP which are further developed jointly. IAMAP can also coordinate on an international basis university research which is outside the influence of WMO.

3. IAMAP structure

Ten Commissions within IAMAP, which coordinate scientific work and organize topical symposia, have the following areas of scientific interest.
— Atmospheric chemistry and global pollution
— Atmospheric electricity
— Climate
— Cloud physics
— Dynamic meteorology
— Meteorology of the upper atmosphere
— Ozone
— Planetary atmospheres and their evolution
— Polar meteorology
— Radiation

In addition the IAMAP Executive and Secretariat give guidance to the Commissions and organize major meetings such as the Scientific Assemblies, held every four years, usually in collaboration with other IUGG Associations.

4. Fifth Scientific Assembly

The Fifth IAMAP Scientific Assembly is to be held at the University of Reading from 31 July to 11 August 1989.

This Assembly will have four components: invited overview lectures, four major symposia, thirteen topical symposia and a variety of workshops.

The *overview lectures* are to be given by speakers chosen by the Presidents of the Royal Meteorological Society and IAMAP.

The four *major symposia*, each lasting 4 to 5 days, deal with The Global Weather Experiment — 10 years later, middle atmosphere sciences, global energy and water fluxes, and atmospheric trace constituents and climate/global change.

The *topical symposia*, each lasting from one to three days, are concerned with — aerosol and cloud effects on climate, atmospheric transparency, boundary-layer parametrization and larger-scale models, influences of polar regions on global climate, Martian meteorology, mesoscale analysis and forecasting incorporating now-casting, mesoscale processes in extra tropical cyclones, meteorological and chemical aspects of tropospheric air quality, noctilucent clouds, non-linear dynamics and atmospheric flow, remote sensing in polar regions,

remote sensing of trace constituents, and the Earth's radiation budget.

Finally one- or two-day *workshops*, with limited participation, on the following topics are planned — global data sets, International Satellite Land Surface Climatology Project, interpretation of satellite and radar imagery, needs and opportunities for observational studies and numerical prediction models of mesoscale weather systems, and noctilucent clouds.

In the second week of the Assembly a commerical exhibition, METEX '89, will be held for exhibitors to demonstrate their products.

Staff from many establishments in the United Kingdom with an interest in meteorology and atmospheric physics — the Universities of Reading, Oxford, Cambridge and Southampton, the Institute of Hydrology, Natural Environment Research Council, European Centre for Medium-range Weather Forecasts, British Antarctic Survey and the Meteorological Office — are involved in organizing the meetings and in making local arrangements for the many delegates who are expected to attend.

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Reviews

The climate of China, by M. Domrös and G. Peng. 169 mm × 248 mm, pp. xiii+361, *illus*. Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, Springer-Verlag, 1988. Price DM 228.00.

The authors of this book have set themselves the substantial task of providing a full account of the climate of China for the international community. Therefore, after a summary of the data available and an interesting sketch of existing work on the subject, they briefly review China's geography. For readers unfamiliar with China, this chapter would have benefited from the inclusion of regional topographical maps with names of towns, rivers, etc. to clarify the many geographical statements later in the book.

The chapter on the basic atmospheric circulation contains much useful background information for the geographer and climatologist. The description of the atmospheric circulation features associated with the *mei-yu* (plum) rains is of particular interest.

Having established the geographical and broad-scale dynamical controls on China's climate the authors proceed to present the behaviour of individual climatic elements, of which temperature and precipitation occupy the longest chapters. Much that is of interest emerges, such as the summary of the evidence for the 'Little Ice Age' (*c*. AD 1450–1850) and other historical climatic fluctuations, the analysis of precipitation as a function of elevation, and the studies of mountain and valley breezes. There are, however, some shortcomings of interpretation. The greater lapse-rate between Garze and Nagqu (p. 116) is likely to be because Nagqu is in a frost-hollow, as suggested by its greater diurnal ranges (see Appendix). Chengdu's small diurnal range (p. 121) results from its cloudiness (see Appendix). The authors could have commented on why percentage cloud and percentage sunshine regularly exceed 100 as evidenced by the data in the Appendix. In Tables 7.4 and 7.5 they could have represented valley breezes better using afternoon data. In Chapter 9, the diurnal range in the tropics should have been described as greater relative to the annual range, not in absolute terms.

The final two chapters are on the climate classification and division of China, and on China's climate zones, and are useful background material for the geographer and climatologist, and, no doubt, for agriculturalists, economists and ecologists too. The concluding Appendix of climatological statistics gives quantitative support to the entire text, though its introductory table could have been clarified by providing units (e.g. centimetres for snow depth) and by full definitions of the parameters (e.g. snow depth is the maximum, not the average, according to the main text). Also, the monthly 'average' temperatures do not equal the mean of the daily maxima and minima — it would be useful for their interpretation to know how they were calculated. The station numbering system is very helpful.

Unfortunately the text is often difficult to read, or inconcise, and is occasionally confusing. Ideally, the book should have been independently language-edited. Examples of the need for this are the use of 'passates' on page 28 for trade-winds, the expression 'meager climatic importance of temperature variability' on page 122, the confused final paragraph of Section 5.3.1, the use of 'exposition' for 'exposure' on page 191, and the ambiguous title to Figure 7.3. There are also some printing errors and numerical inconsistencies involving, for example, the criteria for the dryness index on page 196 and resulting in confusion between the text and Figures 5.21 and 5.22 as to which periods were dry and wet.

As a general reference and for background study, this book is to be recommended. For precision and scientific incisiveness, a subsequent edition would be welcomed. This could also take advantage of new types of information now available on China's climate such as radiosonde profiles and satellite imagery. In the meantime, the book is a welcome sign of growing international co-operation in climatology.

D.E. Parker

Multiprocessing in meteorological models, edited by G.-R. Hoffmann and D.F. Snelling. 170 mm × 247 mm, pp. xvi+438, *illus*. Berlin, Heidelberg, New York, London, Paris, Tokyo, Springer-Verlag, 1988. Price DM 118.00.

This book collects together the papers presented at two workshops held at the European Centre for Medium-range Weather Forecasts (ECMWF) in 1984 and 1986 on the subject of parallel processing in meteorological models. There are 26 papers from contributors who are experts in the fields of numerical modelling and computer science. The topics covered are wide ranging and include descriptions of parallel computers and their applications, parallel algorithms and programming languages, multi-tasking aids, user experience and thoughts on the future direction of numerical weather prediction. The book also contains summaries of the open sessions at each of the workshops which discuss the programming and computer requirements for meteorological modelling in the future.

As stated in the cover notes, the time-critical nature of numerical weather prediction has ensured that the major weather forecasting centres have always had access to the most powerful computers available. Since the current level of technology (and eventually the speed of light) limits the speed of a single processor, parallel computations have become necessary in order to achieve large increases in performance. The current generation of supercomputers, such as those manufactured by Cray, generally contain a small number of very powerful vector processors which may be used in parallel. Experience with these types of computers forms the subject matter of the majority of the papers in the book. The trend towards massively parallel architectures is also recognized and is discussed in several of the papers.

One of the fundamental questions discussed at the workshops is how to compare the performance of parallel computers of differing architectures in a meaningful fashion. Several of the papers consider ways of measuring the intrinsic vector and multi-tasking performance of parallel processing computers, either by the use of simple measures based on specific combinations of instructions, or by the use of benchmark programs constructed from numerical weather prediction models. Both of these methods have their drawbacks; simple performance measures can sometimes be misleading when used to predict the performance of a large program, while the effort required to optimize a large meteorological model for a particular computer is usually so great that true comparisons are difficult to obtain. Nevertheless, despite these caveats, these papers do provide a useful insight into the performance potential and limitations of a range of computer designs.

The design of efficient algorithms for parallel systems along with techniques for maximizing multi-tasking performance are examined by many of the authors. A variety of practical tools for analysing the overheads incurred and the degree of parallelism achieved when writing multi-tasked code are also presented.

Some of the most interesting papers are those which report hands-on experience of multi-tasking large meteorological models. Perhaps it is a sign of recent history, that all of these are for Cray computers. The two papers documenting the ECMWF experience in multi-tasking their spectral model on Cray X-MP computers are quite illuminating. ECMWF was the first centre to multi-task its operational model and these papers chart their experience and the refinements made to their multi-tasking strategy over the period of the workshops. There are also contributions from other centres on the plans for multi-tasking their models, which provide a wider perspective on possible ways of multi-tasking operational codes.

In general, this collection of articles is well produced and illustrated. Unfortunately, a few of the papers, written by authors for whom English is not their first language, contain inappropriate words or phrases which make certain passages difficult to read and this detracts from the overall quality of the product. Because of the rapidly evolving nature of the subject, some of the computer systems referred to in the book are no longer manufactured and indeed some have never reached the market place. It is therefore regrettable that it was not possible to publish these articles closer to the dates of the workshops. Nevertheless, the book contains a wealth of interesting and useful information which is highly relevant to users of today's supercomputers, providing a rare insight into the use of parallel processing in time-critical applications.

I expect that those people actively involved with multi-tasking meteorological models will find the papers in this book most useful. The contents also form a valuable introduction for someone new to the field. However, the main interest in the book may come from outside the meteorological community, from those areas of engineering and science which are only now thinking about using large parallel computers for the first time.

A. Dickinson

Books received

Atmospheric tidal and planetary waves, by H. Volland (Dordrecht, Boston, London, Kluwer Academic Publishers, 1988. Dfl.210.00, US$99.00, £59.00) is for workers in meteorology, middle atmosphere and space physics, and deals with global-scale dynamical processes within the whole depth of the atmosphere. The concept of the separation of atmospheric flow into eigenmodes on the sphere is used extensively in the analysis of observed global fields. Forcing functions are identified and equations governing the vertical and meridional structure are derived.

Satellite photograph — 18 January 1989 at 1217 GMT
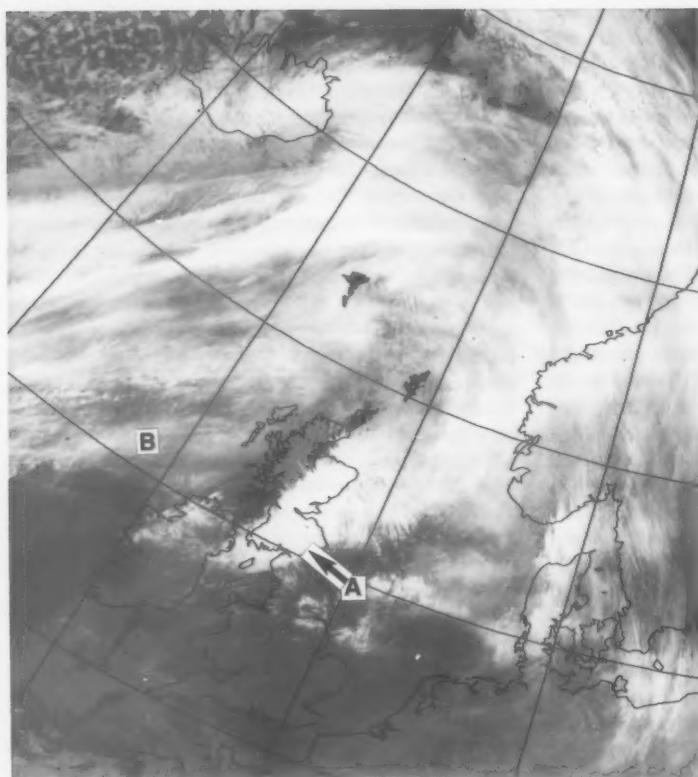
Photograph by courtesy of University of Dundee.

An anticyclone was centred over southern England with a broad south-westerly flow over the northern part of the British Isles. An extensive area of orographic cirrus cloud, labelled A, was situated over the northern part of the British Isles. This was the subject of a study using the Hercules aircraft of the Meteorological Research flight. Visual observation from the aircraft showed that the cloud extended from an altitude of 24 000 ft to approximately 40 000 ft (above the altitude of contrails formed by commercial air traffic).

Upwind, time-lapse picture sequences showed that cirrus, labelled B, was dissipating due to descending motion produced by the orographic flow (Fig. 1). Ahead of the leading edge of the orographic cirrus, lee-wave motions with a wavelength of around 12 km were clearly visible in the altostratus layer. The leading edge was itself marked by stacks of individual lenticular clouds. Further downwind, these spread into layers which eventually merged. The Hercules made a number of runs alongwind into the cirrus edge at about 57° 30′N to observe the formation and growth of cloud particles at different temperatures.
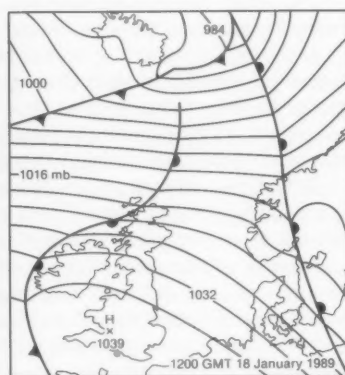
The nature of the cirrus remained largely unchanged between 0830 GMT when it was first noted during the pre-flight briefing and about 1500 GMT when the aircraft left the area. Traces of it were still visible at 0200 GMT on the following day.
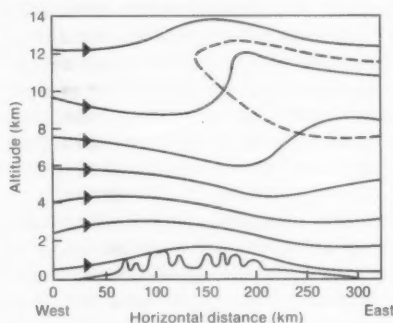
Figure 1. Schematic cross-section showing streamlines of the airflow over northern Scotland. Smaller scale lee-wave motions are not shown (after Reid, S.J., Long-wave orographic clouds seen from satellites. *Weather*, **30**, 1975, 117–123). The region contained by the dashed line shows the location of the orographic cirrus.

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe the results of research in applied meteorology or the development of practical forecasting techniques.

Preparation and submission of articles

Articles for publication and all other communications for the Editor should be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ and marked 'For *Meteorological Magazine*'.

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately.

Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary*.

References should be made using the Harvard system (author, date) and full details should be given at the end of the text. If a document referred to is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to.

Tables should be numbered using roman numerals and provided with headings. We consider vertical and horizontal rules to be unnecessary in a well-designed table; spaces should be used instead.

Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and difficult to read. Keep notation as simple as possible; this makes typesetting quicker and therefore cheaper, and reduces the possibility of error. Further guidance is given in BS1991: Part 1: 1976 and *Quantities, Units and Symbols* published by the Royal Society.

Illustrations

Diagrams must be supplied either drawn to professional standards or drawn clearly, preferably in ink. They should be about 1½ to 3 times the final printed size and should not contain any unnecessary or irrelevant details. Any symbols and lettering must be large enough to remain legible after reduction. Explanatory text should not appear on the diagram itself but in the caption. Captions should be typed on a separate sheet of paper and should, as far as possible, explain the meanings of the diagrams without the reader having to refer to the text.

Sharp monochrome photographs on glossy paper are preferred: colour prints are acceptable but the use of colour within the magazine is at the Editor's discretion. In either case contrast should be sufficient to ensure satisfactory reproduction.

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